8.1 Funicular Shell as Foundation Elements

The studies conducted on individual funicular shells have clearly shown that the failure of the shell is initiated mainly by the cracks developed on its edge beams due to flexure, shear or tension or a combination of any of these. Therefore, it is considered worthwhile to investigate the use of funicular shells as units in multiple shell foundations with suitable connecting elements which prevent premature development of cracks on edge beams, before the allowable compressive stresses in the shell is reached. As the most common types of foundations are isolated footings, rafts and strips, the use of funicular shells was investigated as elements of these foundations. In all these cases, it was found that the shell elements can replace the slab with considerable economy.

8.2 Footings

For footings of columns especially on soft soils for two or three storeyed buildings, it is necessary to distribute the column load over a large area so as to limit the soil pressures within allowable limits. As an example, a column transmitting 30t to the soil will require 5.71sq.m of footing area to limit the soil pressure to 5.2t/m². If funicular shells of 1.1mx1.1m size are used as shown in Fig 8.1, with proper connecting elements over the edge beams of the shells, the area of the multiple funicular shell
footing will be 5.76sq.m. The column can be taken from the centre of the connecting beams. They transmit the column load to the edge beams of the shells through which shells receive the load. The shell element, in turn, disperses the load to the foundation soil. The design of the connecting elements have to be done, treating them as cantilevers to take up the stresses due to bending moments, shear forces and torsion, if any, induced by the soil reaction on the shells. The central connecting beams will have to be designed as cantilever beams to take up the soil pressures acting on the areas ABC, EFG and EABF. The edge beams are cantilevered from the ends of the central connecting beams. They will be designed to take up the soil pressures acting on the area DEC. (Fig 8.1.).

To assess the performance of such footings, multiple funicular shell footings of four shells were tested in the laboratory test bed of 200t capacity.

8.3 Preparation of the Test Bed and Assembly of the Shell Units

The sand in the test bed of the 200t capacity loading frame was compacted to the required density in layers of 15cm thickness so that the average relative density of the sand was 0.35 having a density of 1.63gm/cc. Then the positions of the funicular shells in the unit were marked. The bed was approximately shaped by scooping out sand very carefully to receive the convex faces of the shells. Then the individual shells were placed in position.
to see that perfect contact was established between the soil and the shell surfaces. The tops of the edge beams of the shells were at the same level and there was a space of 20cm left in between the shells. After placing the shell in position, the space in between the shells were also filled with sand. Then, the formwork was set in position for the connecting beams and their reinforcements were bent, tied and put inside it. Concreting was done using a nominal volumetric concrete of mix 1:2:4, using well graded aggregate of maximum size 20mm. Concrete cubes 15cm x 15cm x 15cm were cast for each batch of concrete mix. The concrete was allowed to cure for a minimum period of 28 days before testing.

For every test, the entire process was repeated all over again.

8.4 Tests on Multiple Funicular Shell Footings on Bed of Sand with Relative Density 0.35

Tests were conducted in the laboratory test bed of sand with relative density 0.35 on multiple funicular shell footings with shell models 30cm x 30cm size and 60cm x 60cm size and prototype shells of 110 x 110cm size.

8.4.1 Test on multiple funicular shell footing with shell models, 30cm x 30cm size

The connecting elements of the shell footing with four shell models were designed in such a way that it behaves as a rigid foundation. The details of the footing and its elements used are given in Fig 8.2. The test bed
was prepared as detailed earlier in section 8.3 and the unit cast over it. After curing it for 28 days, the footing tested by reaction jacking. The loads were applied in increments of 227kg (500lbs). The settlements of various points in the footing were observed for each increment of load. The load settlement graphs of various points of the footing was as given in Fig 8.4. Till the load reached a value of 10t, the footing had almost uniform settlement. When the loading was continued beyond 10t, a fine crack developed along the diagonal of a shell in the unit (Fig 8.3). The test was stopped at that stage. The footing behaved almost as a rigid one till the end of the test, as seen from load-settlement graphs.

8.4.2 Test on multiple funicular shell footing with shells of 60cm x 60cm size

The connecting elements of the footing units were designed to the combined capacity of the four shells in the unit (assuming 2.25t as the capacity of one shell). The details of the footing unit were as given in Fig.8.5a. The unit behaved almost rigidly till the load reached a value of 8t as seen from the load settlement graphs of the test (Fig.8.5b). Beyond the load of 8t, the load point showed larger settlements than the other points in the unit. When the load was above 10t, the relative settlements between the load points and the other points also increased. At a load of 14.1t, fine cracks appeared at the bottom of the junction of the central connecting beams. On increasing the load further, the relative settlements between the load point and
the other points also became significant and the cracks widened. At 18.18t, load cracks appeared at the junctions between the central connecting beams and the connecting beams along the edges. Further, fine cracks were observed on the edge beams of the shells also at this load. On loading the unit further, the cracks from the edge beams of the shells continued into them. At 20.9t load, the cracks in the shells widened considerably, indicating imminent collapse of the unit. The test was stopped at this stage of loading.

8.4.3 Test on multiple funicular shell footing I with prototype shells of 110cm x 110cm size

The details of the footing unit were as given in Figs.8.6a. The optimum design of a footing element is realized when the connecting elements, the shells, and the foundation soil fail simultaneously. This is a very difficult objective to be accomplished in practice. As a trial, the connecting elements were provided with suitable dimensions and reinforcements to achieve the above objective. The details of the shuttering work and reinforcements are given in Fig.8.6b.

The loads were applied at the centre through the connecting elements in increments of 5t. The settlements of various points in the unit were measured for each increment of load. From the beginning of loading, the load point settled more than any other points in the footing. As the loading increased, the rate of differential settlements also
increased as seen from the load settlement graphs (Fig 8.7). When the load reached 25t, fine cracks appeared at the bottom of the central connecting beams at their junction. Beyond 25t load, the rate of settlement of the load point also increased. At 28.6t load, cracks started appearing at the bottom of the junctions between the central connecting beams and those along the edges. Lifting of corners of the footing was observed when the load reached a value of 29t. There were marked changes in the rate of settlements of all the other points of the footing and the cracks on the connecting elements widened on loading further. At 36.8t load, cracks started appearing on the edge beams of the shells near their corners. As load was increased further, the cracks on the connecting elements widened and those on edge beams of shell proceeded on to the shells. When the load was 42.4t, the cracks on the shell widened considerably, indicating the imminent collapse of the unit. At this stage, loading was stopped. The crack patterns on the unit at the end of the test were as shown in Figs. 8.8a to 8.8d.

8.5 Discussion of Results of Tests on Footings on Sand with Relative Density of 0.35

The multiple funicular shell footing with shell models failed at a load of 10 t when one of the shells yielded along its diagonal (Fig. 8.3). The average contact pressure at this stage was 15.625 t/m², assuming uniform contact pressure distribution. The connecting beams of the unit at the load point were subjected to a bending moment of
0.5 t-m only at the final load of 10t, whereas the ultimate moment of resistance of the beams was 2.16 t-m (Table 8.1). Further, the connecting beams were intact and the footing unit had almost uniform settlement (Fig. 8.4), thereby indicating that the connecting elements behaved rigidly during the test. In general, the performance of the footing showed that the assumption of a rigid footing was correct.

In the case of shell footing with 60 cm x 60 cm size shells and 110 cm x 110 cm size shells, the ultimate moment capacity of the central connecting beams were 3.138 t-m for the former and 5.439 t-m for the latter. The first cracks at the bottom of the connecting beams at the junctions near the load point were observed at loads of 14.1t and 25.0t respectively. The bending moments to which the central connecting beams were subjected to at these loads were 1.4 t-m for the former and 4.58t for the latter, assuming uniform contact pressure distribution below the footings. Thereafter, the relative settlements between the load points and centres and corners of the connecting beams along the edges progressively increased (Fig. 8.5b. and Fig. 8.7). This resulted in the loss of proper composite action of the unit due to these deformations. At loads of 18.18t in the case of the former and 36.8t in the case of latter shell units, cracks appeared on the edge beams of the shell in their corners. On further loading, the relative settlements between the various points in the unit also increased and the cracks from the edge beams of the shell continued to the shell. When the loads reached values of
20.9t for 60 x 60 cm shell unit and 42.4t for 110 cm x 110 cm shell unit, the cracks widened (Fig.8.8a) indicating imminent collapse of the shell. At these loads, the tests were stopped. However, it was observed that the compressive stress in the shells at the collapse loads in the units were much less than the permissible ones.

The load settlement graphs of these tests showed some distinctive trends. The footings with model shells had almost uniform settlement till the end of the test (Fig.8.4). The connecting elements of the footing unit with 60cm x 60cm size shells did not undergo appreciable relative settlements between various points in the initial stages of the test. But beyond 14.1t load, they showed loss of composite action with an increasing trend in differential settlements, thus decreasing their effectiveness in transferring the loads to the individual shells. The settlements of the load points also increased progressively, indicating greater concentration of stresses below the load points till the end of the test. In the case of footing with prototype shells, there were relative settlements between the various points of the unit, even for the first increment of load. The trend continued till the end of the test. Beyond the load of 29.0t, lifting of the corners of the connecting elements along edges were observed (Fig.8.7). On further loading, there was a clear change in the slopes of the load settlement graphs of the various points in the unit. The load point had large settlements. This was clearly indicative of the central connecting elements.
becoming progressively ineffective in transferring the loads to the entire shells and concentration of soil stresses immediately below the load points.

The connecting elements were instrumental in enabling the units to be loaded beyond the sum of the capacities of the four shells in footing units with 60cm x 60cm shells and 110cm x 110cm shells. The sum of the ultimate capacities of 4 shells in the units were estimated to be 9t and 16t taking the ultimate capacity of each shell as 2.25t and 4t for the former and the latter respectively.

The units could be loaded to much above these values, before the collapse of the shells in them because of the action of the connecting elements. These not only keep the shells in proper position, but also impart additional strength to the shells in the unit as follows.

When the footing units are loaded, the soil reaction acting on the shell induces tension in the edge beams of the shell. The tensile stresses also increase with loading. When the edge beams of the shell undergo small tensile deformations, the frictional forces between the connecting elements and the edge beams are mobilized to resist the same. The strains in the edge beam is consequently reduced. When the connecting elements deflected progressively upwards after development of cracks on them, the contact between them and the edge beams decreased considerably, the latter were free to deform under the tensile stresses. The details of the tensile forces
induced and the forces resisting them in edge beams of the shell at the loads when tension cracks appeared on the edge beams are given in Table 8.2.

From Table 8.2, it is clear that the onset of cracks on the edge beams near the corners of the shell started when the tension induced in them exceeded the forces resisting them.

Moreover, the connecting elements were also imparting additional flexural strength to the edge beams of the shells to take up bending moments till they yielded. This led to the development of more cracks on the edge beams of the shell due to the combined action of bending and shear. The connecting elements were also instrumental in preventing any lateral deflection of the edge beams of the shell, if any, till they yielded.

Since the compressive stresses induced in the shells were less than the permissible ones, it is believed that, if the connecting elements had not yielded, the cracks on the edge beams of the shell would not have developed paving the way for the ultimate collapse of the footing units. This led to the conclusion that the connecting elements could be designed suitably to transmit the column loads to the foundation soil through them and the shell units taking into account the allowable bearing capacity of the soil and the allowable compressive strength of the concrete in the shell.
The settlements of the load point were considerable beyond 29t load, thereby indicating high concentration of contact pressures in the central region towards the latter part of the test. This was due to the fact that the foundation soils were compressible and the connecting elements flexible. High pressures at the central region result in densification of the soil due to the large settlement. Consequently, this resulted in a redistribution of the stress progressively. Thus, the pressure distribution below the foundation unit is expected to have a convex shape with maximum ordinate at the centre and almost zero value near the edges of the footing.

8.6 Test on Multiple Funicular Shell Footing II on Dense Sands with Rigid Connecting Elements

The studies on different units of multiple funicular shell footings on sands with low relative density revealed the fact that they behaved differently depending on the rigidity of the connecting elements and contact pressures. The footing unit with model shells behaved almost rigidly whereas the one with prototype shells with flexibility, for their dimensions and soil pressures. Therefore, it was thought fit to investigate the performance of a footing unit consisting of prototype shells with connecting elements of greater rigidity on sands with high relative density of 0.78. Figs. 8.9a and 8.9b show the details of the footing unit tested. The connecting elements were designed in such a manner that the unit could
be loaded to more than twice the combined capacities of the four shells in the unit, namely 32t.

The unit was cast in the test bed of the 200t capacity loading frame. After the curing period, the test was conducted. Initially, loads were applied in increments of 2.27t (5000lbs) with measurements of settlements of the footing at salient points. Till the load reached a value of 45t, the footing performed satisfactorily. Above this load, fine cracks appeared at the bottom of the junction between the central connecting beams. When the load was above 55t, fine cracks appeared at the junctions between the central connecting beams and those at the edges. With increase in load, the cracks on the connecting elements widened and at 65t load, cracks appeared on the edge beams of the shells. On continuation of loading, these cracks proceeded on to the shells in a similar fashion as in the case of the footing unit tested on loose sand bed. When the load reached a value of 67.27t (148000lbs) the cracks on the shells widened. During further addition of load, the unit showed higher rates of strains and at 68.18t (150000lbs) the test was stopped. The load settlement graphs for the tests are given in Fig.8.10.

8.7 Analysis of Test Results

The footing unit performed properly till cracks appeared at the junction between the central connecting beams when the load reached a value of 45t. Further, cracking of the connecting elements took place with increase
in load and at 65t load cracks appeared on the edge beams of the shell. The load of 65t was more than four times the combined capacity of the four shells in the unit. The cracks in the edge beams were initiated when the connecting elements became ineffective in preventing tension developing in them and in imparting additional rigidity to them at this load. Above this load, cracks from the edge beams of the shells continued on to them leading to their ultimate collapse. Assuming uniform pressure distribution, the compressive stress induced in the shell was worked out to be 49.1kg/cm\(^2\) at load of 65t. Therefore, it is deduced that by suitably designing the connecting elements, the shells could be put to its optimum use. As an example, if the allowable compressive stress in concrete is 40kg/cm\(^2\), the maximum load to which the unit could be subjected to will be 51.22t. The connecting elements consequently should be designed to transmit loads to this extent only. This will be an ideal solution if the allowable bearing capacity of the soil corresponds to this applied load.

8.8 Performance of Footings on Loose Sand and Dense Sand

The relative rigidity between the foundation structure and soil had significant effect on the average total and differential settlements of the footing units in all the tests.

Of the various sizes tested, the one with model shells performed as a nearly rigid one. The unit had almost uniform settlement till the end of the test.
In the case of footings with prototype shells on loose sands and dense sands, the load settlement graphs clearly showed that the units did not behave as rigid units during any part of the test. The differences were in the magnitudes of settlements which would, naturally, be expected to be high for loose sands and low for dense sands. However, the trend of the load-settlement graphs of various points in the shell units were similar for both the cases, except for the lifting of the corners of footing in loose sands beyond the load at first crack on the central connecting beams. This showed that the contact pressure distribution diagrams had presumably convex shapes with a maximum at the centre and minimum near the edges with larger concentrations of stresses at the centre for loose sands than the dense one. To ensure smaller settlements and near uniform pressure distribution, rigid connecting elements will have to be provided for the units. Incidentally, this will put the connecting elements to its optimum use designed under the assumption of uniform contact pressures.

For the footing units tested, these was no mechanism to bind the shells and the connecting beam elements over them. They remained seated over the edge beams of the shells till they yielded and had relative movements. If they were connected integrally with the edge beams of the shells, the system can be expected to behave as a single unit with greater rigidity and efficiency. Therefore, it is felt that a series of test using integrally connected footing units, would be helpful to evaluate their
mechanism of failure better. Such a study can be made by providing suitable connecting elements cast in the edge beam of the individual shells, before the connecting beams are cast. It is also possible to make use of precast beams to connect the shell units with provision for grouting to ensure an integral action.

8.9 Limitations of the Tests on Multiple Funicular Shells in the Laboratory Test Bed

The test bed had plan dimensions of 7.5m x 5m and 5m depth. The footing unit with model shells was square in plan with 0.8m x 0.8m dimensions. The footing with 60cm x 60cm size shells and those with 110cm x 110cm size shells had 1.4m x 1.4m and 2.4m x 2.4m dimensions respectively.

It is possible that the test results may be vitiated due to the restraint of the test bed size. In accordance with standards, the width of test bed should be at least 5 times that of the footing element tested. In this study, this condition is satisfied in the case of footings with model shells.

However, it may be pointed out that present studies were primarily intended to probe into the feasibility of multiple funicular shell foundations. As such, there is no doubt that this purpose is satisfied by these tests. The structural behaviour of the shell elements were basically unaffected because the modes of failures of the shells when tested with uniformly distributed load on edge beams and as elements in the footings were almost same.
The behaviour of the connecting elements were typical of cantilever beams acted upon by reaction from the edge beams of the shells.

In terms of quantitative data, it is possible that the behaviour of the foundation soils under the multiple shell footings might have been affected by the following limitations:

i) The slip planes might not have developed fully under the footing.

ii) The friction between the sides of the test pit and the sand in it also might have contributed to the reaction for the applied load through the foundation elements.

iii) The zone of influence of smaller intensities of foundation pressure might have intersected the sides of the test pit.

In actual practice however, it is not easy to have a test bed of 7m or 12m width uninterrupted by columns or walls to satisfy the requirement either in the field or in the laboratory. The test results obtained will have to be considered as the best possible under these circumstances.
<table>
<thead>
<tr>
<th>Details of the shell footing unit</th>
<th>Moment of resistances of central connecting elements</th>
<th>Ultimate moment of resistance of central connecting elements</th>
<th>Load at first crack on connecting elements</th>
<th>Load at first crack on edge beams of shells or on shells</th>
<th>Load at which test was stopped/ultimate load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footing with shell models 30cm x 30cm</td>
<td>0.499</td>
<td>2.159</td>
<td>Did not crack</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Footing with 60cm x 60cm size shells</td>
<td>1.0</td>
<td>3.138</td>
<td>14.1</td>
<td>18.18</td>
<td>20.9</td>
</tr>
<tr>
<td>Footing with 110cm x 110cm size shells</td>
<td>1.9474</td>
<td>5.439</td>
<td>25.0</td>
<td>36.8</td>
<td>42.4</td>
</tr>
</tbody>
</table>

Table 8.1 Details of the moments of resistance (elastic and ultimate) of connecting elements of footings and loads at important stages of tests
<table>
<thead>
<tr>
<th>Details of footing</th>
<th>Load at first crack on edge beams of shell</th>
<th>Contact pressure</th>
<th>Tensile force induced in the edge beam</th>
<th>Frictional force developed between the edge beams and connecting elements</th>
<th>Ultimate tensile strength of edge beam</th>
<th>Total forces resisting tension induced in edge beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footing unit with 60cm x 60cm size shells, 4 numbers</td>
<td>18.18</td>
<td>0.9275</td>
<td>2547</td>
<td>683</td>
<td>1679</td>
<td>2362</td>
</tr>
<tr>
<td>Footing unit with 110cm x 110cm size shells, 4 numbers</td>
<td>36.90</td>
<td>0.6388</td>
<td>3650</td>
<td>1347</td>
<td>1679</td>
<td>3026</td>
</tr>
</tbody>
</table>

Table 8.2 Details of tensions induced and force resisting them in edge beams of shells in footing units
Depth of edge beam is made less than 1:10 or equal to 1:10.

ELEVATION

Funicular shell 110cm X 110cm size.

Central Connecting beams

Slope of the edge beam is made less than 1:10 or equal to 1:10.

Edge beams of footing.

Depth of edge beam at the centre of footing.

Central Connecting beam

PLAN

FIG. 8.1. TYPICAL SET UP OF A MULTIPLE FUNICULAR SHELL FOOTING 2.4m. SQUARE WITH FOUR SHELLS - 110 X 110cm. SIZE.
Central Connecting beam 15 cm. deep.
Edge beam 10 cm. deep of the footing.
Funicular shell 30 cm x 30 cm. size.

ELEVATION

Edge beams of the footing 15 cm. wide.
Shell model.
Central connecting beams 30 cm. wide.
Shell model.

PLAN

FIG. 8.2 DETAILS OF MULTIPLE FUNICULAR SHELL FOOTING 0.8m. SQUARE WITH FOUR SHELL MODELS.
FIG. 8.3. MULTIPLE FUNICULAR SHELL FOOTING
WITH MODEL SHELLS OF 30 cm. x 30 cm.
SIZE TESTED IN THE LABORATORY.
FIG. 84 LOAD SETTLEMENT GRAPHS OF LOAD TEST ON MULTIPLE FUNICULAR SHELL FOOTING—SHELL SIZE 30CM × 30CM
FIG. 8.5a. DETAILS OF MULTIPLE FUNICULAR SHELL FOOTING 1.4m. X 1.4m. SQUARE WITH FOUR SHELLS 60cm X 60cm. SIZE.
FIG. 8.5b. LOAD SETTLEMENT GRAPHS OF LOAD TEST CONDUCTED ON MULTIPLE FUNICULAR SHELL FOOTING WITH 60cm x 60cm SIZE SHELLS
Central connecting beam.

Funicular shell 110 cm x 110 cm size.

ELEVATION

Central connecting beam.

Edge beams of footing.

Funicular shells 110 cm x 110 cm size.

PLAN

FIG. 8.6a. DETAILS OF MULTIPLE FUNICULAR SHELL FOOTING 1 2.4 m. SQUARE WITH FOUR SHELLS 110 cm. X 110 cm. SIZE.
FIG. 8.6.b. ARRANGEMENT OF REINFORCEMENTS AND FORMWORK FOR CONNECTING BEAMS AND EDGE BEAMS OF MULTIPLE FUNICULAR SHELL FOOTING I.
Fig. 8.7 LOAD-SETTLENT GRAPHS OF TEST CONDUCTED ON MULTIPLE SHELL FOOTING WITH SHELLS OF SIZE 110CM × 110CM
FIG. 8.8a. MULTIPLE FUNICULAR SHELL FOOTING I
WITH PROTOTYPE FUNICULAR SHELLS OF
110 cm x 110 cm. SIZE TESTED IN LABORATORY.

FIG. 8.8b. CRACK PATTERNS IN SHELL 1 AND
CONNECTING ELEMENTS OF MULTIPLE
FUNICULAR SHELL FOOTING I.
FIG. 8.8c. CRACK PATTERNS IN SHELL 2 AND CONNECTING BEAM AND EDGE BEAMS OF MULTIPLE FUNICULAR SHELL FOOTING I

FIG. 8.8d. CRACK PATTERNS IN SHELL 4 AND CONNECTING BEAM OF MULTIPLE FUNICULAR SHELL FOOTING I
FIG. 8.90A MULTIPLE FUNICULAR SHELL FOOTING
FIG. 8.9. DETAILS OF MULTIPLE FUNICULAR SHELL FOOTING II, LOADING AND LOCATIONS OF SETTLEMENT DIAL GAUGES.
FIG 8.10 LOAD-SETTLEMENT GRAPHS OF TESTS ON MULTIPLE FUNICULAR SHELL FOOTING WITH SHELLS OF SIZE 110CM x 110CM, DENSE SAND BED OF RELATIVE DENSITY = 0.8